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The Role of the Seabed in Low-Frequency Shallow-Water Acoustic Propagation: Examples from Measurements and Modelling

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ABSTRACT

Except in rather unusual circumstances, interaction with the seafloor is an inevitable accompaniment to the propagation of sound in the sea. In shallow water, especially at very low and low frequencies, the bottom interaction plays a significant, if not deterministic, role in acoustic propagation. From the results of numerous experiments and numerical modelling in recent years, it is evident that one must account for the geoacoustic properties in more than an *ad hoc* fashion. Some of the relevant research efforts, particularly those from the ongoing research program at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL), are described in this paper. The results of the NOARL measurements in several geographical areas, coupled with numerical modelling, are used to demonstrate the significance of energy partitioning between waterborne and bottom paths, the role of Scholte interface waves, the efficacy and limitations of selected numerical models, and the significance of ambient noise.

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CONTENTS

The Role of The Seabed in Low-Frequency Shallow-Water Acoustic Propagation: Examples From Measurements and Modelling

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Except in rather unusual circumstances, interaction with the seafloor is an inevitable accompaniment to the propagation of sound in the sea. In shallow water, especially at very low and low frequencies, the bottom interaction plays a significant, if not deterministic, role in acoustic propagation. From the results of numerous experiments and numerical modelling in recent years, it is evident that one must account for the geoacoustic properties in more than an *ad hoc* fashion. Some of the relevant research efforts, particularly those from the on-going research program at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL), are described in this paper. The results of the NOARL measurements in several geographical areas, coupled with numerical modelling, are used to demonstrate the significance of energy partitioning between waterborne and bottom paths, the role of Scholte interface waves, the efficacy and limitations of selected numerical models, and the significance of ambient noise.

INTRODUCTION

The propagation of sound in the sea is generally accompanied by some degree of interaction with the seafloor. In deep water, or for high frequencies, it is often sufficient to view the interaction as one of reflection or perhaps scattering of acoustic energy. However, in shallow water, or for very low frequencies (VLF, approximately 20 Hz and below) the seafloor may become an integral part of the propagation medium. In particular, the decreased attenuation at the lower frequencies results in the transfer of relatively large amounts of acoustic energy into the seabed. As a result, the "acoustic waveguide" is no longer bounded by the sea surface and sea bottom, but extends to some depth (dependent upon frequency) into the bottom sediment, and, possibly, basement level. Under these circumstances, the properties of the sea bottom and subbottom, particularly shear and compressional sound speeds and attenuations, are crucial determinants of the behavior of the sound propagation. Conversely, the characteristics of the propagation provide clues to the nature of the bottom material (geoacoustics). For example, the deeper penetration of large-wavelength VLF sound enables the structure of subbottom layering to be investigated, particularly in view of the inherent dispersion attributable to the layering.

Scholte interface waves also play a role in underwater acoustic propagation, notably in shallow water and/or in the VLF regime. The behavior of these waves is strongly dependent on seabed (especially shear) properties. As a result these waves and others provide useful information on the environmental parameters controlling the propagation, including ambient noise.

These questions and others have formed the basis of an ongoing program in VLF acoustic propagation at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL). The results and methods discussed in this paper derive primarily from this research program. Therefore, a few words on the NOARL program, including a description of a "typical" VLF experiment, are presented next. The remainder of the paper is devoted to a discussion of the salient points of acoustic propagation in the ocean, particular emphasis being placed on the role of the sea bottom.

I. THE VLF PROGRAM OF THE NAVAL OCEANOGRAPHIC AND ATMOSPHERIC RESEARCH LABORATORY

The basic objective of NOARL's VLF program is the understanding of the propagation characteristics of VLF signals and ambient noise, with particular emphasis on energy partitioning among the water, bottom, and subbottom propagation paths.

A typical experimental configuration is shown schematically in Figure 1. The environment was generally characterized by a sloping bottom, the nature of which varied from site to site; water depths ranged from 100 meters to several thousand meters. The sensors consisted of a vertical string of hydrophones (generally 16) and a distribution of several (as many as 15) ocean bottom seismometers (OBS). The hydrophones were spaced more closely than half-wavelength and spanned either the entire vertical extent of the water column, or a fraction of it. Each OBS consisted of a set of tri-axial geophones and an external hydrophone. A continuous wave (CW) source (10 Hz and 15 Hz), airgun clusters, and explosives were used as sound sources. The CW source has the advantage of a repeatable output (source) level, easily obtained phase information (important for variability studies), and a continuous time response (allowing greater spectral resolution). On the other hand, separation of the multipath arrivals is not possible with a CW signal. The impulsive sources allow this separation and, in addition, provide broadband energy. The hydrophone signals were multiplexed and telemetered via UHF to a nearby ship, where they were converted from analog to digital signals. The OBS signals were recorded on the internal tape recorder and stored for subsequent playback and analysis. The results of the data analysis, coupled with the predictions of numerical models, were used to address the preceding questions.

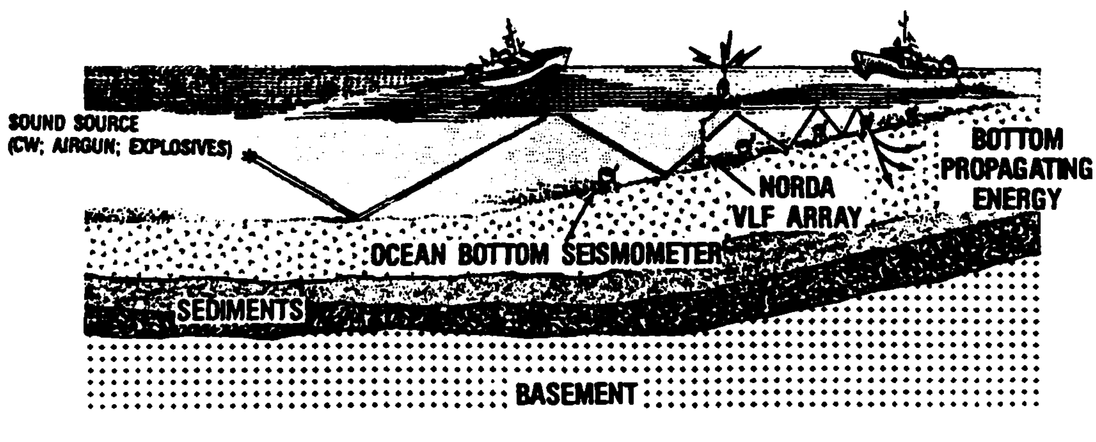

Figure 1. Configuration of a typical NOARL VLF experiment.

II. THE INFLUENCE OF BOTTOM-TYPE ON THE MODES OF PROPAGATION

The nature of the sound propagation in an ocean medium depends both on the bottom material and the angle of incidence of the energy. Energy may propagate either as trapped, discrete, normal modes in the water column or form part of the continuous spectrum in the bottom. The demarcation between discrete and continuous modes is based on the critical angle, $\theta_c = \cos^{-1}(c_w/c_b)$, of the bottom, which depends on the compressional phase velocity in the water column c_w, and the bulk wave speed in the bottom, c_b. For grazing angles (measured with respect to the horizontal) less than θ_c much of the incident energy (all, if the bottom is lossless) is reflected, resulting in the propagation of discrete modes. For grazing angles greater than the critical angle, significant transmission into the bottom occurs, giving rise to continuous modes which, because they decay much more rapidly than $r^{-1/2}$, are largely confined to the near wave field.

Naturally, the partitioning of energy between waterborne and bottom propagating energy depends on the relative values of c_w, and the compressional and shear bulk wave speeds in the bottom, c_p and c_s, respectively.

A. Soft Seabeds

For the case $c_p > c_w >> c_s$, which characterizes soft seabeds, such as unconsolidated sediments or sedimentary rock, significant acoustic energy is transferred from the acoustic waterborne modes to bulk shear waves in the bottom. Since there is no critical angle for shear in this case, this energy "leakage" occurs even for low grazing angles. The waterborne modes are now no longer strictly discrete modes, since as they propagate they decay exponentially with range. They are variously named leaky modes, pseudo-modes, quasi-discrete modes, or virtual modes. Some authors even refer to them as discrete modes. In any case, for low grazing angles these quasi-discrete modes dominate the propagation. As the grazing angle increases, both compressional and shear waves propagate in the sea bottom.

B. Hard Seabeds

In hard seabeds ($c_p > c_s > c_w$) energy loss into the bottom is less significant. In this case there are two critical angles: A critical angle for shear waves, θ_{cs}, and a critical angle for compressional waves, θ_{cp}; $\theta_{cs} < \theta_{cp}$ since $c_p > c_s$.

For grazing angles less than the shear critical angle, θ_{cs}, "total" reflection results in discrete, trapped mode propagation in the water column. For $\theta > \theta_{cs}$, some acoustic energy penetrates the seafloor and is coupled into a shear wave. Although the modes now properly belong to the continuous spectrum, a small leakage out of the waveguide (water column) has a small effect on the modes: this means that the waterborne propagation is quasi-discrete. For even greater grazing angles $\theta > \theta_{cp}$, the acoustic energy is coupled into both shear and compressional waves in the bottom and forms part of the continuous spectrum.

III. SCHOLTE INTERFACE WAVES

For either of the above types of seabed, the ability of the seafloor material to support shear waves allows for the existence of interface modes of propagation.

The role of interface waves in underwater acoustics has received considerable attention in recent years, since these waves serve as a propagation mechanism (of both signal and noise) and as a tool for probing the seismoacoustic properties of the seabed. (See e.g., Rauch (1980)[1], Essen (1981)[2], Schmalfeldt (1983)[3], Ali (1984, 1987)[4,5], etc). These waves, also called surface waves, are characterized by amplitudes which decay exponentially away from the interface between a solid and another medium. Hence, they are effectively restricted to the immediate vicinity of the interface. Since they are a combination of compressional and shear body waves, at least one of the interfaces must be a solid for interface waves to exist. The other medium can be vacuum, liquid, or solid, in which case the corresponding interface wave is denoted a Rayleigh wave, Scholte wave, or a Stoneley wave, respectively. At limiting frequencies the distinction between lowest-order Rayleigh and Scholte waves becomes somewhat arbitrary. In particular, consider the case of propagation in a three-layered medium: vacuum over liquid (thickness h) over a solid half-space. For large wavelengths ($h/\lambda \rightarrow 0$), the liquid layer acts as an insignificantly thin film – i.e., the large wavelength propagation does not "see" the liquid layer. In this case, the phase and group velocities of the lowest mode Scholte interface wave tend to the Rayleigh wave velocity in the solid half-space. On the other hand, for very small wavelengths ($h/\lambda \rightarrow \infty$) the liquid layer is effectively very thick and the lowest mode interface wave propagates as a Scholte wave at the interface between the liquid and solid.

The speeds of interface waves (phase velocities) are always less than the sound speed in the water column and the shear speed in the bottom. In the ideal case of two homogeneous half-spaces in contact, Scholte waves are non-dispersive. Moreover, for unconsolidated sediments (clay, silt, sand) with relatively low shear speeds the Scholte wave speed, c_{sch}, and attenuation, α_{sch} are close, respectively, to the bulk shear wave speed and attenuation, c_s and α_s. In particular, $c_{sch} \cong 0.9c$ and $\alpha_{sch} \cong 1.1\alpha_s$. In realistic media, particularly layered seabeds, the propagation speeds are dependent upon the frequency that is, the propagation is dispersive. The dispersion properties of Scholte waves allow one to obtain information on the properties of the seabed sediments, at least to a depth of one or two Scholte wavelengths. In particular, measured dispersion curves coupled with appropriate numerical results (e.g., synthetic seismograms and dispersion curves) make it possible to determine the shear speed and shear attenuation profiles. It should be noted that the shear properties are of far greater interest than the compressional wave properties since the latter have a negligible effect on Scholte wave propagation.

As noted earlier, interface wave amplitudes decay exponentially away from the interface. As a result, effective direct excitation of Scholte waves requires a source close (of the order of one wavelength) to the interface. At VLF frequencies, particularly below acoustic cutoff, this condition is normally satisfied. As a result, both waterborne sources and wind/wave action at the water surface can lead to the excitation of Scholte waves and hence to the propagation of acoustic energy, including ambient noise, in the seabed and the water column, even at frequencies below the acoustic waveguide cutoff.

Depending on the particular geoacoustic environment, the effects of Scholte waves may extend over a significant vertical portion of the water column (Brooke, 1985[6]; Rauch, 1985[7]). The penetration depth into the seabed of Scholte waves is approximately equal to the Scholte wavelength, which is less than the corresponding water wavelength. Because of the very small attenuation in the water column, however, the penetration of the Scholte wave into the water column may greatly exceed this value. Thus, hydrophones may show the effects of Scholte waves over a significant part of the water column, particularly for high speed (hard) bottoms (for which most of the Scholte wave energy is in the water).

An example of the effect on propagation of interface waves (via the inclusion of shear) is shown in Fig. 2, which was calculated using the SAFARI Fast Field Program (FFP) numerical model. The environment is a 100 m depth isospeed (1500 m/s) duct, with the following properties: compressional speeds of 1750 m/s, shear speed of 500 m/s, compressional attenuation of 0.1 dB/λ_p, shear attenuation of 0.2 dB/λ_s, and a density ratio between bottom and water of 2.0. The source is placed just above the bottom (95m depth) and the receiver is on the bottom. Since the source frequency (5 Hz) is below the cutoff frequency for discrete modes (approximately 10 Hz in this case), one would not expect any significant waterborne propagation in this case. This is confirmed by Fig. 2 (a), which shows the propagating energy vs. wave number (i.e., the FFP integrand, which is related to the Green's function). There are no discrete modes and only

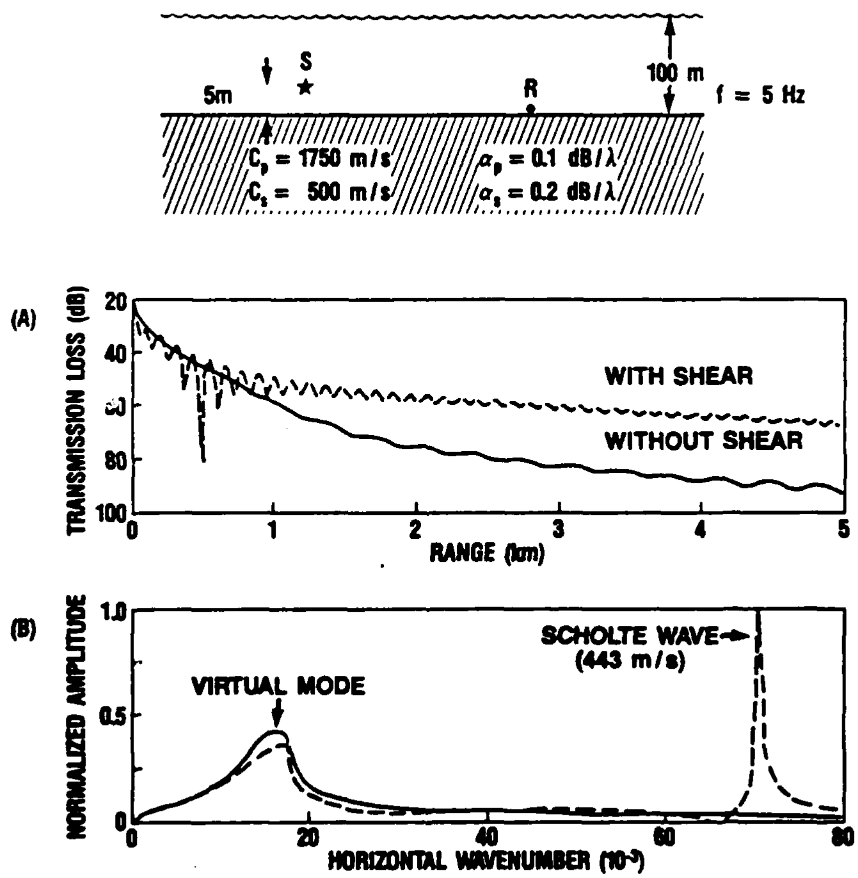

Figure 2. The effect of shear (Scholte waves): (a) transmission loss and (b) wave number spectrum (FPP Integrand).

one highly damped virtual or "leaky" mode. As already noted, continuous (or virtual or leaky) modes correspond to steep propagation angles above the critical angle (here, 33.6°); hence they result in significant transmission into the bottom. However, because they decay much more rapidly than $r^{-1/2}$ they are confined largely to the near field. Thus, in this case, the only viable propagation mechanism is that associated with the evanescent mode, seen as the prominent response at 0.6 m^{-1} wave number, which turns out to be a Scholte interface wave. This is illustrated in Fig. 2 (b), which shows the propagation loss vs. range. If the interface wave is excluded (no shear case) the propagation is very poor, since energy is carried only by the highly attenuated continuous mode. With shear included, the propagation does show some interference with the continuous mode at short ranges, but at longer ranges only the interface mode remains. It is noted that the propagation speed of the Scholte wave is here about 443 m/s. This is consistent with the approximation (valid for a nondispersive environment) that the Scholte propagation speed is about 0.9 of the sediment shear speed. Thus, for very low frequency acoustic propagation, the effect of shear is to enhance propagation. It should be noted, however, that at higher frequencies (above cutoff) shear increases the propagation losses for waterborne propagation, and thereby degrades propagation.

It has already been pointed out that Scholte waves are an effective carrier of ambient noise. Indeed, a considerable portion of infrasonic ambient noise (waterborne and seismic) appears to consist of Scholte waves. The plausibility of this result is suggested by Fig. 3, which compares the seismic noise measured with a tri-axial geophone with the response predicted (using SAFARI) for Scholte wave propagation. The figure clearly suggests that the seismic ambient noise has a behavior that is characteristic of interface wave propagation (the region below about 6 Hz in the theoretical result) and not of waterborne propagation.

An example of recently measured acoustic ambient noise levels is shown in Fig. 4, which provides spectral levels over a period of 1.5 hours. The measurement was made in shallow water

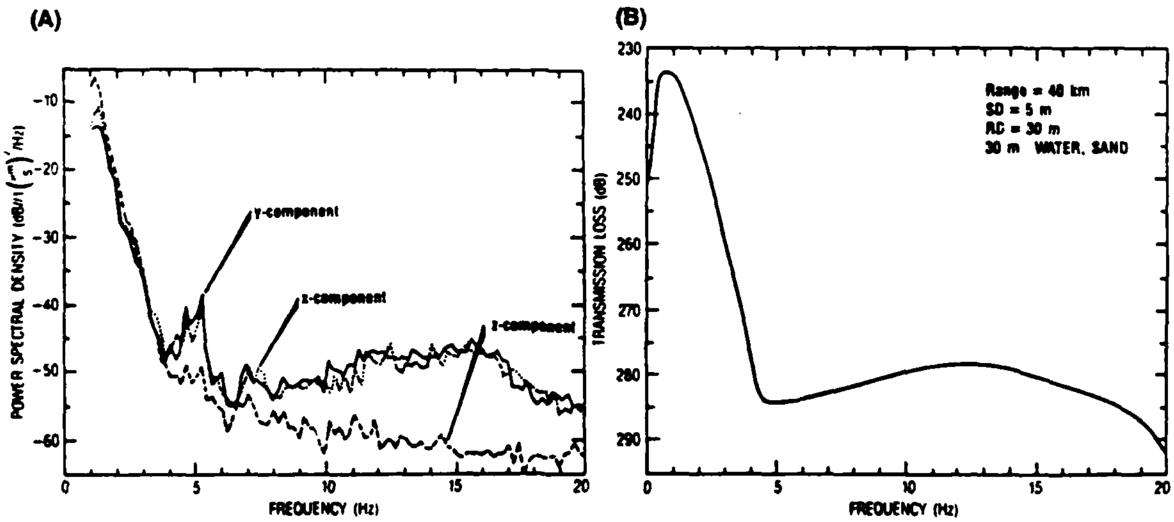

Figure 3. Comparison of (a) experimental seafloor seismic ambient noise (Mediterranean) and (b) the theoretical Scholte wave response.

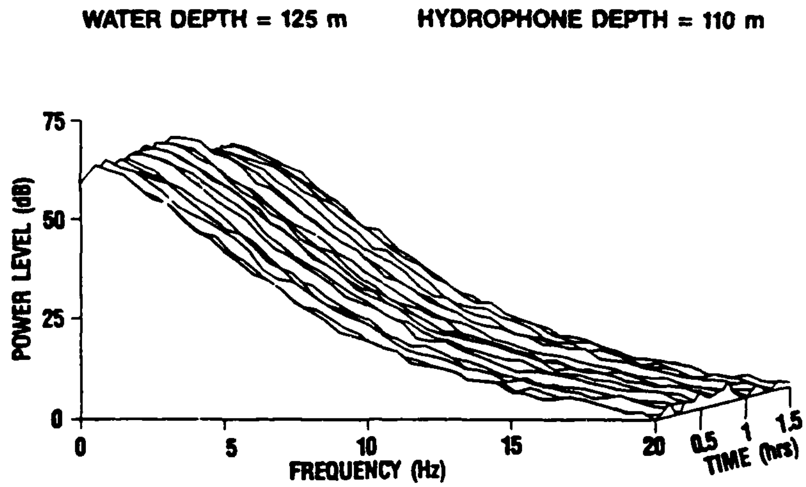

Figure 4. An example of acoustic ambient noise (Gulf of Mexico).

(depth 125 m) in the Gulf of Mexico, off the coast of Louisiana, using a vertical string of hydrophones. The result in Fig. 4 was obtained from the deepest hydrophone (110 m). The steep drop-off in level between 2 or 3 Hz and 10 Hz is quite evident.

IV. THE EFFECTS OF REFRACTING SEDIMENTS IN RANGE-DEPENDENT SEAFLOORS

As already mentioned, the propagation of sound, particularly at low frequencies, is strongly determined by sound speed gradients in the bottom. Fig. 5 provides a quantitative demonstration of this effect, using parabolic equation (PE) numerical models. The PE model is used in this case since it is designed to handle propagation in range-dependent environments (but cannot handle shear wave propagation in the bottom), whereas SAFARI, for example, handles only horizontally stratified environments (but does treat shear waves). The problem represented in Fig. 5 is that of upslope propagation of acoustic energy. A time-harmon : (CW) point sound source of 25 Hz is placed at a starting range (r = 0) and a depth below the ocean surface of 112 m (i.e., $z_s = 112$ m). The transmission loss as the energy propagates upslope is represented by contour levels; the black line represents the ocean bottom. Clearly, as the sound propagates from deep to shallow water the energy decreases from its maximum level near the sound source to lower levels in the water and in the bottom. For Fig. 5(a) the sound speed in the water column is a constant $c = 1500$ m/s, the speed in the sediment is a constant $c = 1704.5$ m/s, the attenuation is $\alpha = 0.5 dB/\lambda$, and the density is $\rho = 1.15$ g/cm. This problem is often referred to as the Jensen-Kuperman problem (1980)[8]. For the conditions of this problem, three trapped (discrete) modes exist at the starting, deep portion (200 m) of the range. It turns out that the source depth ($z_s = 112$ m) is a node point of mode 2; therefore only modes 1 and 3 are excited at this source depth.

The increasing grazing angle of the sound "ray", with increasing distances up the slope, eventually results in sizable penetration into the slope at the critical angle of the bottom. In other words, at the critical angle acoustic energy is converted from the discrete, trapped spectrum into

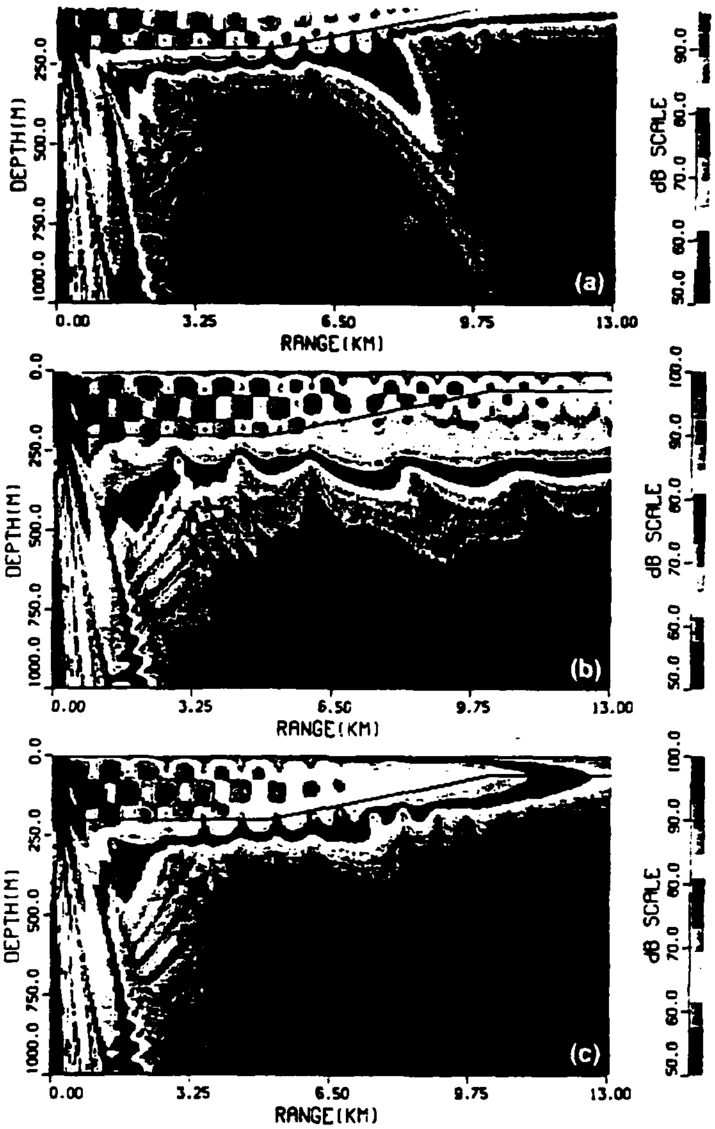

Figure 5. Upslope propagation (a) $g = 0$; $\alpha = 0.5$ dB/λ;
(b) $g = 0.85$/s; $\alpha = 0$; (c) $g = 0.85$/s; $\alpha = 0.5$ dB/λ.

the continuous spectrum. The point in range at which this conversion occurs for the ray corresponds to the cutoff depth of the equivalent mode (Jensen and Kuperman, 1980). Mode 3 cutoff occurs near $r = 7$ km, as is strikingly evidenced by the tongue-like beam penetrating into the sediment. Mode 1 (with a lower grazing angle) continues to propagate beyond the top of the slope. At ranges less than approximately 7 km, an interference pattern between modes 1 and 3 is evident.

Next, we consider the case in which the attenuation is zero ($\alpha = 0$) and, instead of an isospeed sediment, the sound speed gradient, g, is 0.85 s^{-1}. In contrast to the case $g = 0$, there are four trapped modes present at 25 Hz for $d = 200$ m. Once again, the highest mode cuts off near $r = 7$ km. However, the others persist to the top of the incline. A contour plot of transmission loss for a 25 Hz source appears in Fig. 5(b). The downward-propagating beam appearing for $g = 0$

has been replaced by a horizontally propagating beam near z = 250 m. It is seen that the signal at the top of the slope is a few decibels stronger for the refracting bottom. Finally, we consider the realistic case in which both attenuation and a bottom gradient are present. Figure 5(c) illustrates the result for $\alpha = 0.5$ dB/λ and $g = 0.85$ s^{-1}. In this case, we see that the levels towards the top of the slope are reduced, compared with the refracting, lossless bottom (Fig. 5(b)).

We summarize with the following remarks. For upslope propagation, energy penetration into the sediment increases with range. However, a positive sound speed gradient in the sediment prevents deep penetration of this energy, and returns some of it to the water. If attenuation is small in the upper sediment layer, energy that penetrates into the bottom is refracted back into the water column with little loss. One might expect this effect to enhance propagation far up the slope. If attenuation is large in the upper sediment layer, much less energy is returned to the water since rays are attenuated in addition to being refracted in the sediment. Thus, one would expect signals received near the top of the slope to be weak in this case. Additional details are provided in Collins et al (1988)[9].

V. EXAMPLE OF PROPAGATION IN A HORIZONTALLY STRATIFIED ENVIRONMENT

Even in the absence of bottom gradients, significant propagation effects can take place. We consider the results of a SAFARI simulation of propagation measurements made off Cape Fear, North Carolina. The geoacoustic input parameters are shown in Fig. 6(a). Although based on the Cape Fear environment (CTD casts and seismic-derived formation velocities), the parameters are nevertheless a simplification. In particular: gradients in the bottom are not accounted for, the

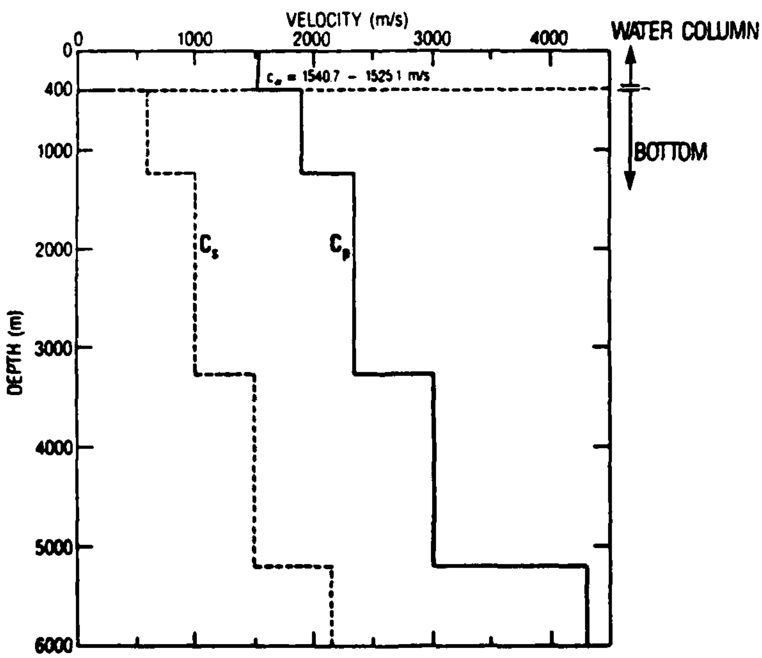

Figure 6(a). Geoacoustic input parameters for SAFARI Model (Cape Fear).

shear values are estimates, and the water depth is assumed to be a constant 400 m (the water depth at the location of the hydrophone string). The result of a pulse calculation using SAFARI is shown in Fig. 6(b). The pulse, with a peak amplitude at 10 Hz and a depth of 85 m, was designed to simulate the response of the explosives used in the experiment. The response with range is plotted against time reduced by 4.3 km/s, the speed of the deepest layer in the model (Figure 6(a)). The waterborne arrivals are clearly dominant, separating with range into 3 or 4 discrete modes. Preceding the water arrivals, the head waves along the various bottom layers are evident, albeit with reduced amplitudes. For source and receivers closer to the bottom than shown here, the model predicts another dominant mode, a Scholte interface wave propagating with a velocity of approximately 523 m/s. This is seen in Fig. 6(c), the SAFARI result for a 10 Hz CW sound source. Apart from the Scholte mode, the three trapped modes and the higher-speed continuous modes are also evident. The transmission loss curve demonstrates that the propagation is dominated by the trapped modes, except in the near field where the Scholte wave is significant.

VI. AMBIENT NOISE

The ambient noise field is often regarded as an unwanted part of the propagation. In fact, however, it does offer the possibility of deducing information on the bottom properties,

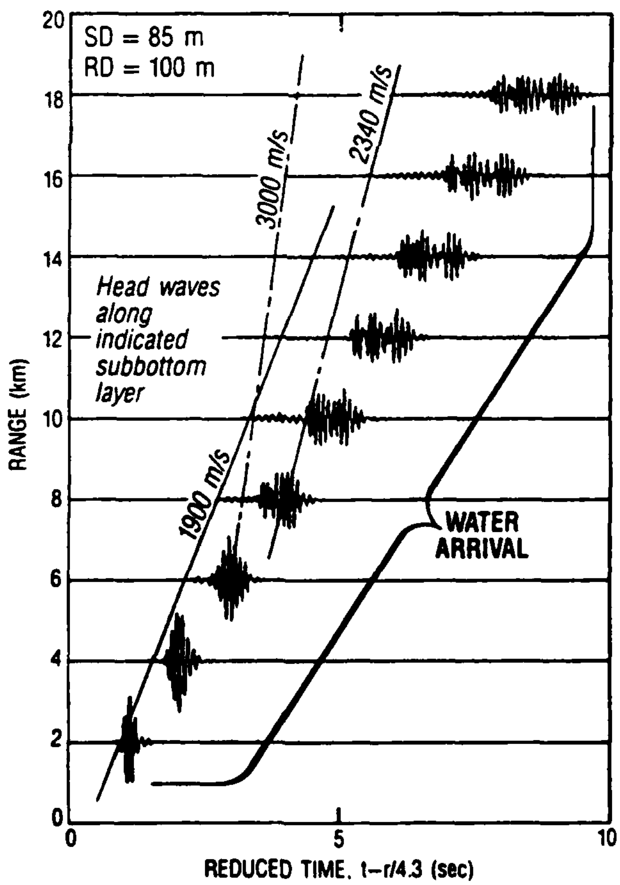

Figure 6(b). Result of a SAFARI pulse calculation for a simplified Cape Fear environment.

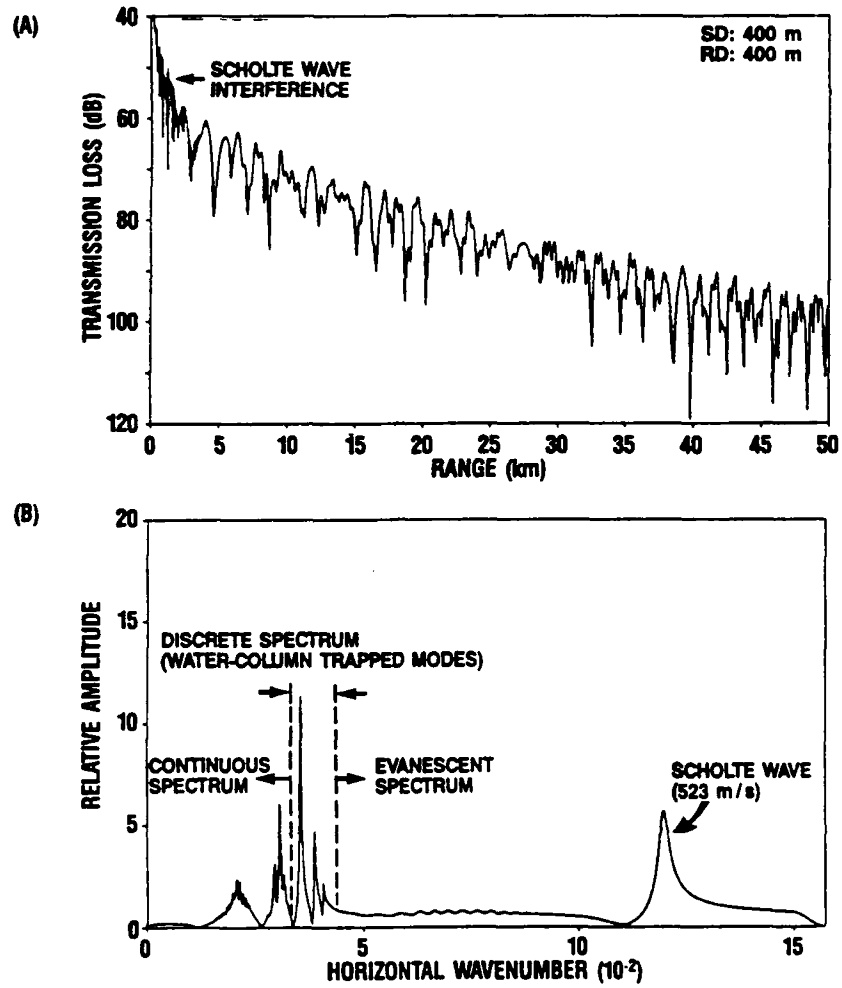

Figure 6(c). Typical SAFARI results for CW (10 Hz) for Cape Fear: (a) transmission loss and (b) wave number spectrum (FFP Integrand).

particularly in shallow water. This is not surprising, since the propagation of ambient noise, no less than that of acoustic signal, is influenced by the sea bottom and the sound speed profile in the water column. Conversely, appropriate measurements of ambient noise can lead to information on these environmental parameters and also on the source mechanisms.

In the past, the need to understand ambient noise was particularly evident in the areas of signal processing, since the noise characteristics — particularly spatial and temporal coherences — set fundamental limits on array gains and signal/noise separation. More recently, an awareness of the significant role of ambient noise is ultra low (< 1 Hz) frequency (ULF) and VLF propagation has led to increased interest in the subject (see references 10 and 11, for example).

In shallow water, both nearby and distant noise sources can be significant. The former may arise from wind/wave action, while the latter are often attributable to distant shipping. The noise from distant sources will most likely arrive in the form of normal (discrete) modes confined to a small angle about the horizontal direction. This can be explained by the fact that energy propagating at steep angles will not survive the attenuation implicit in repeated bottom and surface interactions over long ranges. Buckingham (1987)[12] has shown that the vertical directionality of the ambient noise in shallow water permits the determination of the critical angle of the bottom (in the absence of strong interference from local shipping).

The nearby sources will contribute via the direct path. The direct path propagation, as well as energy arising from bottom interaction at angles steeper than critical, gives rise to the continuous modes referred to earlier. Thus the continuous modes contribute to the vertically propagating noise field.

To properly understand ambient noise behavior an appreciation of the significance of propagation is essential. In particular, in using measured data to determine the actual source spectrum level of the noise sources, it is necessary to account for the propagation effects. For example, in assessing the noise sources in a VLF shallow-water environment the ocean waveguide effect must be "subtracted". Without this correction, the comparison of noise source levels from data obtained in different environments can lead to erroneous conclusions. On the other hand, the apparently large spread in reported ambient noise levels from various geographical test sites becomes considerably reduced once the propagation effects are accounted for (Schmidt, 1988)[13].

CONCLUSIONS

In treating the propagation of VLF sound, particularly in shallow water, the seabed and subbottom must be considered on integral part of the propagation medium. Depending on the bottom type (i.e., the seafloor geoacoustics), shear, compressional, and interface waves in the sediments play an important role in the propagation. At higher frequencies, the conversion from waterborne compressional waves into elastic waves results in increased losses, thereby degrading the waterborne propagation. For very low frequency propagation, on the other hand, the bottom path tends to enhance propagation. Scholte and other interface waves are particularly effective carriers of acoustic energy, including ambient noise, even at frequencies for which discrete waterborne propagation is absent.

Numerical Modelling, using both range-dependent parabolic equation models and full-wave FFP models, coupled with measured data, provides considerable insight into the propagation modes and hence the bottom geoacoustics. In this regard, analysis of dispersion curves and stacked seismograms are particularly informative. Even infrasonic ambient noise carries with it evidence of its interaction with the seabed.

REFERENCES

1. Rauch, D., "Seismic Interface Waves in Coastal Waters: A Review", Report SR-42, SACLANT ASW Research Centre, La Spezia, Italy, 1980.

2. Essen, H. H., Janle, H., Schrimer, F. and Siebert, J., "Propagation of Surface Waves in Marine Sediments," J. Geophysics 49, 1981, pp 115-122.

3. Schmalfeldt, B. and Rauch, D.,"Explosion-Generated Seismic Interface Waves in Shallow Water: Experimental Results," Report SR-71, SACLANT ASW Research Centre, La Spezia, Italy, 1983.

4. Ali, H. B., and Schmalfeldt, B., "Seismic Sensing of Low-Frequency Radiated Ship Noise," Report SR-77, SACLANT ASW Research Centre, La Spezia, Italy, 1984.

5. Ali, H. B., Tango, G. J., and Werby, M. F., "Very Low Frequency Seismic Noise in Shallow Water: Scholte Wave Generation and Propagation at Two Offshore sites," SEG Geophysics Abstracts, 1987, pp 82-85.

6. Brooke, G. H., Thomson, D. J., and Mackinnon, R. F., "Some Characteristics of Virtual Modes in Shallow Water With High Speed Bottom," in *Ocean Seismo-Acoustics*; *Low-Frequency Underwater Acoustics*, T. Akal and J. M. Berkson, Eds. Plenum Press, New York, 1986, pp 233-242.

7. Rauch, D., "On The Role of Bottom Interface Waves in Ocean Seismo-Acoustics: A Review," op cit, pp 623-641.

8. Jensen, F. B., and Kuperman, W. A., "Sound Propagation in a Wedge-Shaped Ocean with Penetrable Bottom," J. Acoust. Soc. Am., Vol. 67, 1980, pp 1564-1566.

9. Collins, M. D., Ali, H. B., Authement, M. J., Nagl, A., Uberall, H., Miller, J. F., and Arvelo, J. I., "Low-Frequency Sound Interaction With a Sloping, Refracting Ocean Bottom," IEEE J. Oceanic Engineering, Vol. 13, No.4, 1988, pp 235-244.

10. Kerman, B. R., Ed., *Sea Surface Sound: Natural Mechanisms of Surface Generated Noise in the Ocean*, Kluwer Academic Publisher, Dordrecht, 1988.

11. Sutton, G. H., Ed., "ULF/VLF (0.001 to 50 Hz) Seismo-Acoustic Noise in the Ocean," Proceedings of a Workshop at the Institute of Geophysics, University of Texas, Austin, November 29 to December 1, 1988 (Draft, 1989).

12. Buckingham, M. J. and Jones, S.A.S., "A New Shallow-Ocean Technique for Determining the Critical Angle of the Seabed From the Vertical Directionality of the Ambient Noise in the Water Column," J. Acoust. Soc. Am., Vol. 81, 1987, pp 938-946.

13. Schmidt, H., and Kuperman, W. A., "Estimation of Surface Noise Level from Low-Frequency Seismo-Acoustic Ambient Noise Measurements," J. Acoust. Soc. Am., Vol. 84, 1988, pp. 2153-2162.

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Except in rather unusual circumstances, interaction with the seafloor is an inevitable accompaniment to the propagation of sound in the sea. In shallow water, especially at very low and low frequencies, the bottom interaction plays a significant, if not deterministic, role in acoustic propagation. From the results of numerous experiments and numerical modelling in recent years, it is evident that one must account for the geoacoustic properties in more than an ad hoc fashion. Some of the relevant research efforts, particularly those from the ongoing research program at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL), are described in this paper. The results of the NOARL measurements in several geographical areas, coupled with numerical modelling, are used to demonstrate the significance of energy partitioning between waterborne and bottom paths, the role of Scholte interface waves, the efficacy and limitations of selected numerical models, and the significance of ambient noise.

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